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Prepared for
U.S. Department of Energy
Assistant Secretary for Fossil Energy

and

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FOREWORD

Fiscal year 1991 completes the eighth year of research established under Cooperative Agreement DE-FC22-60149 between the U. S. Department of Energy (DOE) and IIT Research Institute (IITRI) for operation of the National Institute for Petroleum and Energy Research (NIPER). This FY91 Annual Report, NIPER-664, covers activities dating from October 1, 1990, through September 30, 1991, as authorized under the approved FY91 Annual Research Plan, NIPER-465.

FY91 marked NIPER's first full year of research under the DOE's National Energy Strategy-Advanced Oil Recovery Program (NES-AORP) and Advanced Oil Recovery Program Implementation Plan (AORPIP). The Plan, issued April 1990, outlines an integrated, highly targeted research, development, and demonstration program focusing on near-, mid-, and long-term objectives to maximize the economic producibility of the domestic oil and gas resource and to assure that new and advanced recovery technologies are implemented in the field within the earliest possible time frame.

NIPER also performs research for the DOE's Advanced Extraction and Processing Technology (AE&PT) Program which is developing crosscutting tools, techniques, and scientific/technical understanding—in both extraction and conversion/upgrading technologies—which can be applied to a broad range of petroleum resources. The Program conducts exploratory research to identify and test novel concepts, and fundamental applied research to develop and apply improved technical and scientific understanding to the solution of generic problems.

This Annual Report provides research accomplishments, publications, and presentations resulting from the FY91 research conducted under 14 Base Program projects, 11 of which were funded under DOE's Light Oil and Heavy Oil Programs, and three funded under the AE&PT Program.

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I. INTRODUCTION

Fiscal year 1991 completed the eighth year of research under a cooperative agreement established in 1983 between the Department of Energy (DOE) and IIT Research Institute (IITRI) for operation of the National Institute for Petroleum and Energy Research (NIPER). Research programs at NIPER cover a wide spectrum of specific technical tasks, all of which relate to three broad technology areas: (1) enhanced oil recovery (EOR) and all of the associated technical activities such as reservoir characterization and imaging techniques; (2) alternative fuels evaluation and testing, including the supporting technologies of thermodynamics research and fuels characterization; and (3) environmental technology related to production, transportation, and utilization of oil and gas. Under the agreement, NIPER's mission has three major thrusts: the first and primary is to perform work for DOE's Office of Fossil Energy (FE) through an approved Base Research Program; second, to conduct research work through a Supplemental Government Program (SGP) for non-DOE government agencies and any additional work for DOE not included in the Base Program; third, to help industrial clients solve their technical problems through a Work for Others (WFO) Program. The Bartlesville Project Office (BPO), which is collocated with NIPER, serves as the DOE administrator of the cooperative agreement.

FY91 marked NIPER's first full year of research under DOE's National Energy Strategy-Advanced Oil Recovery Program (NES-AORP) and Advanced Oil Recovery Program Implementation Plan (AORPIP). The Plan, issued in April 1990, outlines an integrated, highly targeted research, development, and demonstration program focusing on near-, mid-, and long-term objectives to bring new and advanced recovery technologies to the field within the earliest possible time frame. The goal of the new plan is to maximize the economic producibility of the domestic oil and gas resource. The near-term objective (fully effective within 5 years) is to preserve economic access to productive portions of the remaining oil resource by instituting a well-designed technology transfer program—involving the Federal government, the states, service companies, and various research organizations—to ensure that currently proven technologies are made available to oil and gas producers who might benefit from their use.

The AORPIP details a reservoir classification system identifying reservoir classes having the greatest recovery potential and with the greatest danger of early abandonment. The DOE estimates that meeting the near-term objective could result in production of an additional 15 billion barrels of oil that might otherwise be lost. With successful technology transfer over the near term, DOE projects an additional 61 billion barrels of oil may become recoverable in the mid term (fully effective within 10 years) by implementing currently identified, but yet-to-be-proven technologies. Here, the DOE takes a problem-solving approach that will maximize specific reservoir producibility by describing reservoir heterogeneities, architecture and flow paths; reservoir simulation and process design; and testing and evaluation of production technologies. The long-term effort, expected to reap benefits the first part of the 21st century, is to develop sufficient fundamental understanding of geoscience and new and novel recovery techniques so that additional oil can be recovered from the 265 billion barrels that remain after near- and mid-term objectives are met.

The AORPIP authorizes continued research in five principal categories: (1) reservoir description methods, tools, instrumentation, and modeling; (2) extraction techniques to include reservoir simulation and advanced secondary and tertiary recovery; (3) environmental technology covering air, water, solid wastes, and wetlands management; (4) petroleum chemistry/processing covering constraints on production and refining problems; and (5) technology transfer.

Under an approved Base Program, NIPER provides supporting research in nearly all of the above categories, and the work is performed and managed under the organization structure shown in figure 1. The Energy Production Research (EPR) Department is responsible for a total of 12 projects in the areas of Geotechnology, Chemical and Microbial EOR, and Thermal and Gas EOR. These projects address categories 1 and 2 of the supporting research outlined above. The Fuels Research (FR) Department is responsible for two Base Program projects in category 4.[1] Presently, no environmental work (category 3) is being performed under the Base Program but several projects are ongoing under the SGP and WFO Programs. A considerable portion of the present environmental work is the result of expertise gained under former Base Program projects. Category 5, technology transfer, is NIPER's principal product and will be emphasized throughout this report since it plays a crucial role in the successful implementation of the AORPIP.

As shown in table 1, 11 of the EPR projects are funded under FE's EOR Light and Heavy Oil Programs. The remaining project (BE12), and the two projects in Fuels Research are funded under FE's Advanced Extraction and Processing Technology (AE&PT) Program.[2] The role of the AE&PT Program is to develop crosscutting tools, techniques, and scientific/technical understanding—in both extraction and conversion/upgrading technologies—which can be applied to a broad range of petroleum resources. The Program conducts exploratory research to identify and test novel concepts, and fundamental applied research to develop and apply improved technical and scientific understanding to the solution of generic problems. Accordingly, the Program directly supports the Office of Fossil Energy strategic goal of environmentally acceptable liquid fuel options. The DOE programs are managed by the BPO which has been delegated the lead assignment in implementing FE's EOR and AE&PT Programs through a number of projects executed by (1) NIPER, which utilizes the federal equipment and facilities at Bartlesville; (2) industrial and university research organizations; and (3) National Laboratories.

The FY91 research accomplishments, publications, and presentations for each of the 14 Base Program projects are presented in this report (information on ordering DOE reports prepared by NIPER is provided in Appendix A). First, however, a brief synopsis of NIPER's involvement in certain facets of DOE's AORPIP will be presented.

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[1] *NIPER is not performing fuels/engines research for DOE under the Base Program although such a category is shown in figure 1 for the Fuels Research Department. The fuels/engines work is, however, important to NIPER's total program as it provides information on the changes and overall acceptability of today's transportation fuels.*

[2] *Individual research projects are numbered in a simple code: A letter "B" representing the Base Program; a letter "E" or "FR" representing the EPR and FR Department, respectively; and a project number. Thus, BE1 indicates Base Program project No. 1 of Energy Projection Research.*

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ORGANIZATION

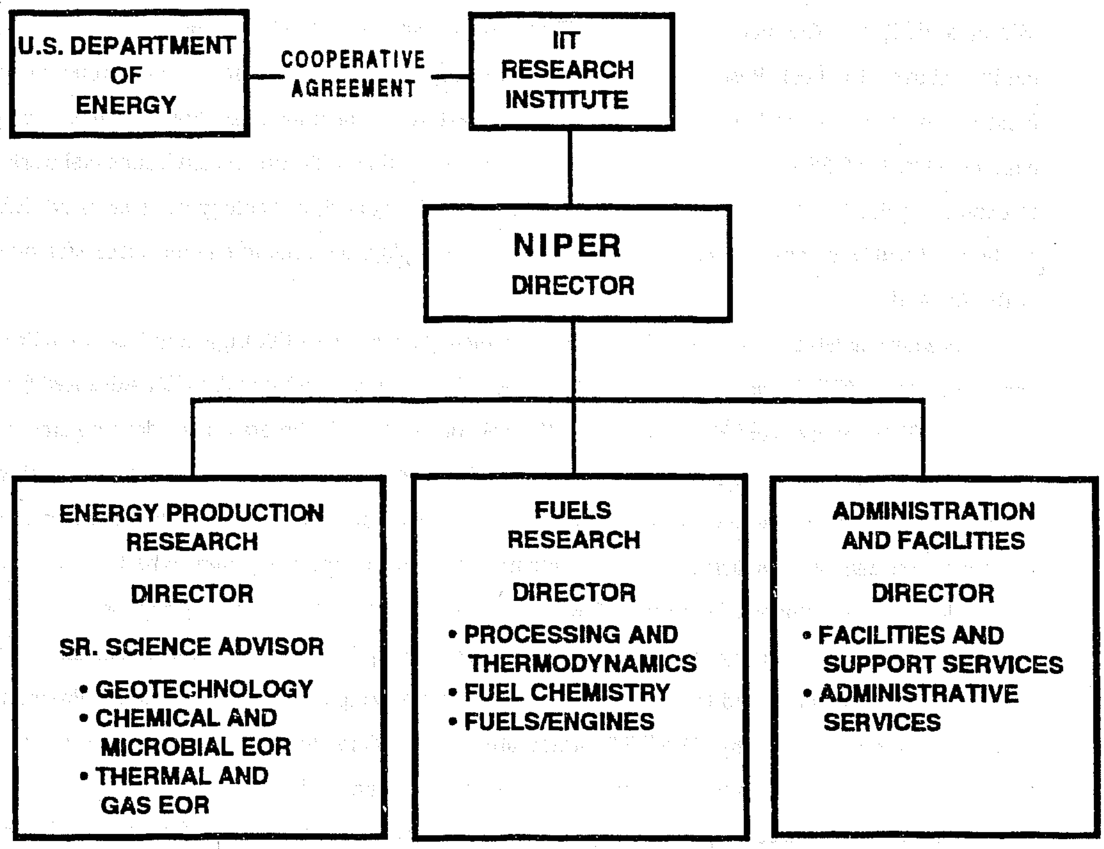

FIGURE 1. - NIPER Organization

TABLE 1. - NIPER FY90 Base Research Program

Project		DOE FE Program[1]	Funding, $K
ENERGY PRODUCTION RESEARCH			
Geotechnology			
BE1	Reservoir Assessment and Characterization	EOR-LO	800
BE2	TORIS Research Support	EOR-LO	340
BE9	Three-Phase Relative Permeability	EOR-LO	300
BE12	Imaging Techniques Applied to the Study of Fluids in Porous Media	AE&PT	545
Chemical and Microbial EOR			
BE3	Development of Improved Microbial Flooding Methods	EOR-LO	300
BE4A	Development of Improved Surfactant Flooding Methods	EOR-LO	600
BE4B	Development of Improved Alkaline Flooding Methods	EOR-HO	150
BE4C	Development of Improved Mobility-Control Methods	EOR-LO	200
Thermal and Gas EOR			
BE5A	Gas Flooding	EOR-LO	200
BE5B	Mobility-Control and Sweep Improvement in Gas Flooding	EOR-LO	440
BE11A	Thermal Processes for Light Oil Recovery	EOR-LO	300
BE11B	Thermal Processes for Heavy Oil Recovery	EOR-HO	250
	Total EPR Base Projects		4,425
FUELS RESEARCH			
Processing and Thermodynamics			
BFR3	Thermochemistry and Thermophysical Properties of Organic Nitrogen- and Diheteroatom-Containing Compounds	AE&PT	350
Fuel Chemistry			
BFR2	Development of Analytical Methodology for Analysis of Heavy Crudes	AE&PT	300
	Total FR Base Projects		650
	TOTAL BASE PROJECTS		**5,075**

[1] Abbreviations: EOR = Enhanced Oil Recovery; LO = Light Oil; HO = Heavy Oil; AE&PT = Advanced Extraction and Processing Technology

Meeting the Objectives of the AORPIP

In August of 1990, Robert H. Gentile, Assistant Secretary for Fossil Energy, appointed a Task Force to put into place the new AORPIP. One of the first activities of the Task Force, comprised of technical and management expertise, was to gather a consensus opinion from industry, academia, and government on issues relevant to oil recovery from fluvial-dominated deltaic reservoirs which were given Class 1 priority for study under the plan. To address these issues, DOE authorized the formulation of a symposium, entitled "Opportunities to Improve Oil Productivity in Unstructured Deltaic Reservoirs," which was held in Dallas, Texas, in January of 1991. Under the direction of Edith C. Allison, DOE's Manager for Class 1 Reservoirs, NIPER assisted in formulating the program and provided an analysis of the results (DOE/NTIS Rpt. No. DE91002237). The analysis identified several major areas to be assessed in furthering the objectives of the AORPIP: (1) technical constraints affecting resource producibility and the research needed to overcome them; (2) required technological advancements in the areas of reservoir characterization, numerical simulation, EOR recovery processes, directional drilling technology, and data acquisition and analysis; (3) technology transfer; and (4) communication between different segments of industry and the DOE. NIPER's research is supporting the DOE implementation of these Task Force objectives in the following ways:

Identification of Technical Constraints

In October of 1991, NIPER prepared for DOE a 521-page report, complete with references, summarizing individual EOR process constraints, limitations, and additional research needed to maximize the economic producibility of the domestic oil resource (NIPER Rpt. No. 527). Information was gathered from professional society and trade journals, DOE reports, dissertations, and patent literature to determine the state of the art in EOR and drilling technologies. The impacts of EOR on the environment and constraints on the application of EOR due to environmental regulations were also reviewed. An analysis of well-documented EOR field projects indicated that in addition to the technical constraints, management factors could also contribute to lower-than-predicted oil recovery in some instances. One chapter was devoted entirely to the constraints associated with technology transfer, and recommendations for improved information exchange were provided.

Also during FY91, NIPER prepared for the DOE an updated version of a environmental regulations handbook for EOR (NIPER Rpt. No. 546). The environmental regulations handbook was first published in 1981 and updated in 1983. Because of the perceived constraints in meeting environmental requirements, these documents were designed to assist owners and operators of EOR operations by providing introductory knowledge of state and federal laws, rules, and regulations which may have jurisdiction over their permitting and compliance activities. The new handbook was complemented by a NIPER journal article (*J. Pet. Tech.* v. 43, No. 6, June 1991) that was designed to familiarize practicing engineers and other interested parties with environmental rules and regulations, i.e., air and water quality and hazardous waste disposal, which are of concern when planning thermal EOR processes.

NIPER's thermodynamics laboratory continues research on processing problems brought on by the increased use of heavy crude feedstocks in refinery streams to make up for the shortfall in light petroleum feeds. Because the heavier feeds contain considerable quantities of hetero- and diheteroatomic compounds, polynuclear aromatics, and organometallic compounds—some of which produce reactive components during processing—the production of fuels containing even small quantities of reactive components can cause fuel utilization problems of instability, incompatibility, and gum formation. Thermodynamic properties are being determined, on a priority basis, for those compounds identified as the most troublesome in the refining process and during storage.

Reservoir Assessment and Characterization

One major point widely agreed upon by the Task Force was the importance of reservoir characterization and its relation to data interpretation and effective reservoir management. NIPER is supporting this area through Base Program research and has been involved in developing techniques to predict reservoir variations and in assessing and characterizing reservoirs since 1983. In FY86, a microtidal barrier island system at Bell Creek (MT) field was selected for study. From this work, a combined quantified geological/engineering model was developed and used to identify the types and scales of heterogeneities in the shoreline barrier system at Bell Creek. Based on this model, the influence of various heterogeneities on fluid flow and hydrocarbon trapping was investigated.

To broaden the geological and engineering understanding of comparative aspects of shoreline barrier reservoirs, and to improve the methodologies, a mesotidal shoreline barrier at Patrick Draw (WY) field was selected for study during FY90. By incorporating the Patrick Draw field model into the generalized barrier island model, the product became more broadly applicable. The FY90 work focused on determining the fundamental relationships between geological, petrophysical, and reservoir production/injection characteristics. Another objective was to determine more efficient and economical reservoir characterization and simulation methodologies for shoreline barrier/barrier island reservoirs.

During FY91, characterization of the mesotidal system at Patrick Draw field continued, primarily through work in three areas. First was the continued improvement and quantification of the geological shoreline barrier model for Patrick Draw field. The second area included construction of the engineering model for Patrick Draw through quantification of reservoir characteristics and integration with the geological model. The third area included a geostatistical analysis to aid in estimating interwell reservoir properties in Patrick Draw. This activity provided an opportunity to investigate the strengths and weaknesses of different geostatistical techniques.

Although barrier island reservoirs were chosen as candidates for study several years before the decision was made to classify fluvial-dominated reservoirs as Class 1, they are in the top 10 of priority of classes outlined in the AORPIP. It is anticipated that the methodologies developed from the previous mid-term studies will be applicable to the Class 1 reservoirs.

Numerical Simulation—Data Acquisition and Analysis

DOE's Tertiary Oil Recovery Information System (TORIS) was instrumental in categorizing fluvial-dominated deltaic reservoirs as the first (Class 1) in a series of reservoir classes to be investigated. This information system was adopted and validated by the National Petroleum Council in 1984 and has since been maintained and updated by the BPO. TORIS consists of comprehensive reservoir data bases to include field test information resulting from DOE cost-shared and tertiary incentive projects (TIP), reservoir/geological engineering data on domestic oil fields, detailed engineering and economic evaluation predictive models; and reservoir data bases. The analysis of fluvial-dominated deltaic reservoirs was based on 410 such reservoirs within the TORIS system. Although originally targeted to the EOR potential of immobile oil, TORIS was expanded in 1990 to investigate the recovery potential of unrecovered mobile oil as well.

NIPER supports TORIS by providing data from the TIP projects, by performing analyses on the system's numerical simulators, and by establishing trends in the application of the various EOR processes. These analyses provide the DOE with improved versions of the simulators before they are distributed, and the TIP and trends data provide DOE information on significant changes in EOR technology utilization. The retrieval of reservoir-specific data for defined targets will continue to be an important task for NIPER. With the expanded emphasis on reservoir-specific research, the requirement for accurate retrieval of reservoir data, based on individual reservoir characteristics, is increasing; and, at the same time, the data are becoming more complex as the number of users increases. Summarized data that are appropriate for modeling are sometimes in conflict with data appropriate for reservoir characterization; thus, the development and implementation of a multi-use reservoir data base management system will be an important future task.

The DOE EOR predictive models are a part of TORIS and are used in most major studies. The credibility of these studies is based on the statistical accuracy with which the model can duplicate the results of numerous EOR projects. Since histories of some projects are difficult to obtain, no statistical application of the modeling results has been made. However, such an analysis is now possible for the incentive projects using data acquired by NIPER over the past 10 years.

In addition to the support for TORIS, NIPER researchers have developed a number of improved simulators based on the BOAST black oil simulator which is available in the public domain. Several major oil companies are now using NIPER's BEST simulator (modification of BOAST) and BEST VHS (vertical/horizontal/slanted well) simulator. The newest simulator, PC-BEST is based upon the above simulators but contains a number of enhancements. The PC version is operable on a personal computer and enables sophisticated simulation of petroleum reservoir problems at a fraction of the cost of commercial simulators. It is ideal for the consultant, independent producer, or field engineer. NIPER's BEST-GEL simulator, also recently developed, is a unique tool that enables sophisticated simulation of gel/polymer floods in heterogeneous petroleum reservoirs. It is also capable of modeling tracer tests and can be used to simulate typical field problems and laboratory corefloods for isothermal Darcy flow in three dimensions under three phases: gas, oil, and water. This simulator is particularly well suited to the consultant, independent producer, or field engineer having problems of early water breakthrough from reservoirs with channeling.

EOR Recovery Processes

DOE's AORPIP classifies recovery processes under two categories, i.e., unrecovered mobile oil (UMO) extraction processes and enhanced oil recovery (EOR). Mobile oil is the unswept reservoir oil that remains after water or gas flooding because of barriers to fluid flow, and extraction processes used in its recovery include infill drilling, polymer flooding, permeability profile modification treatments, and selected combinations of these processes. Immobile oil is that trapped in reservoir rock by a variety of chemical and physical forces and cannot be moved by waterflooding. The recovery of immobile oil relies on EOR processes such as the injection of miscible gases, chemicals, or heat.

NIPER's improved oil recovery research covers both EOR and UMO processes, and the work focuses primarily on advanced technologies which DOE defines as methods presently undergoing laboratory and/or field testing but yet not widely available for commercial applications. NIPER's Base Program research is designed to overcome technical and economic constraints and to improve the predictability and performance of EOR processes. The program has combined efforts directed at DOE analysis and planning activities, support research, and field work. It provides (1) phased field analyses that identify near-term opportunities for operators and the needs for risk reduction for mid- and long-term opportunities, (2) application of technical advances to specific reservoirs, (3) continued research directed toward improving the understanding of the mechanisms of EOR processes, and (4) technology transfer directed toward operators to generate interest in the opportunities identified in the field analysis and supporting research work by NIPER and other organizations.

Technology Transfer

The Task Force elaborated on the importance of technology transfer between research organizations, industry, and the states in meeting mid- to long-term objectives of the AORPIP. NIPER is fully aware of this need and makes contributions of technical information by way of the client programs; through technical publications and presentations; sponsoring and cosponsoring symposia, meetings, and conferences; supplying data base support and development to both DOE and industry; redesigning and improving reservoir simulators; participating in related professional society and association activities; cooperating with other oil-producing countries through DOE-sponsored programs; and working closely with independent oil producers through the SGP and WFO Programs.

During FY91, assistance was provided the DOE in formulating the Third International Reservoir Characterization Technical Conference scheduled for November 3-5, 1991, in Tulsa, Okla. The proposed agenda for this meeting included an opening address by Dr. Donald A. Juckett, director of the DOE Office of Geoscience Research and luncheon addresses by Denise Bode, president of the Independent Petroleum Association of America (IPAA) and Farouk Al-Kasim, consultant, Stavanger, Norway. Tutorials were scheduled for presentation by Noel Tyler and Robert Finley of the Bureau of Economic Geology, University of Texas at Austin; Mohan Kelkar, University of Tulsa; Jack Caldwell, Schlumberger; and Lawrence Teufel, Sandia National Laboratories. Over 240, scientists, engineers, and oil producers were expected to attend this conference.

During May and June of 1991, NIPER's FR Department performed an evaluation on 22 light-duty pickup trucks involved in the Society of Automotive Engineers' Natural Gas Vehicle Challenge. Determinations were made on combustion emissions, fuel consumption, vehicle starting at -5° F, and vehicle safety. The Challenge offered college students the opportunity to show their engineering skills in converting standard gasoline engines to dedicated natural gas operations. Other functions of the Challenge were performed by Argonne National Laboratory and the Oklahoma Energy Center at the University of Oklahoma.

NIPER's capabilities in monitoring gas-powered vehicles and dual-fuel, gas-gasoline powered vehicles are also being extended to the field. Studies are underway on a portion of the 186 dual-fuel vehicles at Tinker Air Force Base and a representative number of the 52 gas-powered vehicles of the Tulsa (OK) School System. In addition to vehicular testing, NIPER is providing technical assistance to Oklahoma's Tri-County Technical School (Washington County) which is developing a course for CNG (compressed natural gas) certification.

NIPER's Petroleum Product Surveys provide fuel property values that are significant both in the manufacture of fuels and in the design of nearly all types of end-use equipment, from small heaters and boilers to jet engines. Biennial reports on motor gasoline (winter and summer) and annual reports on aviation turbine fuels, heating oil, and diesel fuel oils are distributed to some 700 clients which include fuel manufacturers, fuel marketers, designers of heating systems, the military, and consultants. This statistical information is useful in forecasting fuel quality, compiling local and national averages of fuel properties, and supplying the data base needs of various regulatory agencies. These surveys have been conducted at the Bartlesville Center since 1918 and were funded by the DOE and its predecessors for several years; however, the data base is now self-sustaining through a multiclient program established in 1986. The American Petroleum Institute has contributed to this program through the years and continues to provide program guidance.

In FY91, the research program accounted for more than 62 publications by NIPER authors, of which 50 were submitted to DOE as program deliverables. The remaining 12 reports were published either in technical journals or symposia proceedings and resulted from information and data acquired from a combination of Base, SGP, and WFO research. On a quarterly basis, newly developed data generated through the Base Program are provided to the DOE for inclusion in its publication, "Quarterly Progress Review of Research on Enhanced Oil Recovery." This report is disseminated by the DOE to more than 2,400 recipients, including major oil companies, independent operators, service companies, consultants, and universities. Approximately 250 copies of the report are distributed internationally.

In addition to the publications, staff scientists and engineers presented over 20 technical papers at national and international symposia. Participation in such meetings is an essential part of continued progress in developing state-of-the-art technologies and promotes technology transfer. On an international scale, NIPER's research is supporting DOE's cooperative research agreement with the Venezuelan Ministry of Energy and Mines through biennial meetings of Annex IV participants. Presentations at these meetings are carefully evaluated as to content and are used to provide direction for future research in light- and heavy-oil steamflooding. Other organizations participating in Annex IV include INTEVEP, Stanford University, and Lawrence Livermore Laboratories.

Improving Communication Between Industry and the DOE

In addition to the interactive communication that results from normal research operations and participation in meetings, conferences, and symposia, etc., NIPER is conducting research on numerous projects jointly funded by DOE and industry. Most of these projects are currently performed under the SGP program and have proved to be beneficial to all participants in that they allow for the rapid dissemination of information, minimize duplication of effort, promote cooperation, and provide a feedback loop for the identification of problem areas and sectors requiring additional research.

One of the most effective ways to develop industry participation in DOE-related research is through the formation of consortia. This type of activity has been successfully established at NIPER for advancing the state of the art in reservoir-condition, multiphase relative permeability measurements applicable to the study of fluid flow behavior in porous media. In addition to facilitating effective technology transfer, the consortium provides industry and DOE the means to leverage research budgets and ensures that the cooperative research is supporting relevant issues on a priority basis.

Technologies developed in NIPER's laboratories are going to the field. During 1990, an expanded microbial-enhanced oil recovery (MEOR) improved waterflood pilot was initiated in Chelsea-Alluwe (OK) field. The project follows a smaller MEOR improved waterflood pilot in Delaware-Childers (OK) field in which oil recovery was improved by a very acceptable 13% over that from waterflooding alone. For both tests, funding was established as a joint-venture between the DOE and independent oil producers under a SGP project. The expanded pilot project is scheduled for completion during the second quarter of FY93. Both of these field tests are in Class 1 deltaic reservoirs.

In another SGP field project, jointly funded by DOE and an independent operator, NIPER is to test its alkaline-surfactant-polymer (ASP) flooding technology in a Class 1 reservoir in Hepler (KS) field. The ASP process results from mid-term fundamental research studies on coalescence phenomena and dynamic interfacial tension behavior which indicated that the addition of a small amount of surfactant to moderately alkaline formulations significantly improved recovery efficiency while minimizing the deleterious effects of alkali-mineral reactions—reactions that occur when fluids are in contact with reservoir rock. If this test is successful, the ability to recover more oil with only a small amount of expensive surfactant should benefit the primary goal of the AORPIP which is to maximize the economic producibility of the domestic oil resource.

II. ENERGY PRODUCTION RESEARCH

In FY91, the Energy Production Research Department (EPR) was responsible for 12 Base Program projects, 19 SGP projects, and 24 projects for clients in the WFO Program. The Base Program research, totally funded by the DOE, has combined efforts directed toward DOE analysis and planning activities, support research, and field work. The proposed program parallels the new advanced oil research program with (1) phased field analyses that identify near-term opportunities or operators and needs for risk reduction for mid- and long-term opportunities, (2) application of technical advances to specific field applications, (3) continued research directed toward improving the understanding of the mechanisms of EOR processes, and (4) technology transfer directed toward operators to generate interest in the opportunities identified in the field analyses and supporting research work by NIPER and other organizations.

In this report, EPR projects are grouped into three major areas of work. *Geotechnology* provides support for DOE's TORIS data bases and conducts research in the areas of reservoir characterization and the quantitative prediction of fluid-flow behavior in reservoirs. The other two areas, *Chemical and Microbial EOR* and *Thermal and Gas EOR* are concerned with improved oil recovery through a better understanding of the basic mechanisms of EOR processes and the application EOR technologies in support of field projects. Physical and mathematical models are developed and used to simulate processes and verify hypotheses derived from laboratory and field data. These models are also used to identify areas requiring additional research.

Geotechnology

The production of unrecovered mobile and immobile oil requires advances in the ability to predict reservoir heterogeneities and flow paths. Mobile oil is the unswept reservoir oil that remains after water or gas flooding because of barriers to fluid flow. A large portion of the unswept oil is a target for advanced recovery methods, but improved geoscientific knowledge and advanced techniques are needed before petroleum engineers can accurately predict its location. Conversely, immobile oil is oil trapped in reservoir rock by a variety of forces and cannot be moved without chemical or physical stimulation.

Through the years, several different EOR techniques have been attempted in more than 800 oil fields. Many have failed to perform as predicted because reservoir variations and flow paths were not well understood. This lack of understanding of reservoir structure and its effects on fluid flow is the single most important technical problem facing oil producers. In most instances, the rock matrix is not homogeneous; rather, it contains heterogeneities that control fluid flow and determine the degree to which the remaining oil and gas can be recovered. NIPER's four projects in geotechnology are addressing problems associated with reservoir characterization and interrelated studies identifying rock and pore structures and fluid flow parameters of reservoirs through computed tomography (CT) imaging, nuclear magnetic resonance imaging (NMRI), and petrographic image analysis. Studies are also designed to advance the technology in measuring two- and three-phase relative permeabilities at reservoir conditions. Accurate reservoir simulations of potential oil recovery cannot be made without reliable relative permeability data. Geotechnology also provides support to DOE's Tertiary Oil Recovery Information System (TORIS), where research is continuing the areas of EOR project and reservoir data base management, EOR project technology trends analysis, and computer simulation.

The FY91 research for EPR's four projects in Geotechnology is presented in the following section. Individual project summaries describe (1) the relationship of the work to the DOE program, (2) important research accomplished during the fiscal year, and (3) process utilization and technology transfer. The projects are addressed in the following order: BE1, Reservoir Assessment and Characterization; BE2, TORIS Research Support; BE9, Three-Phase Relative Permeability; and BE12, Imaging Techniques Applied to the Study of Fluids in Porous Media.

RESERVOIR ASSESSMENT AND CHARACTERIZATION

Principal Investigator:	Susan R. Jackson
BPO Project Manager:	Edith C. Allison
Project No.:	BE1
Funding for FY91:	\$800,000 (EOR-Light Oil)
Period of Performance:	October 1, 1990 - September 30, 1991

Objective

The broad objective of the National Energy Strategy is to reduce U.S. vulnerability to crude oil supply disruptions by expanding domestic oil production capacity and strategic stocks. This goal is addressed by three time-specific objectives that (1) preserve access to reservoirs with high potential that are rapidly approaching their economic limits, in the near-term; (2) develop, test, and transfer the best, currently defined, advanced technologies to operators, in the mid-term; and (3) develop sufficient fundamental understanding to define new recovery techniques for the remaining oil, in the long-term.

NIPER's reservoir assessment and characterization research program incorporates elements of each of these objectives. The shoreline barrier reservoirs under study represent a class of reservoirs, located in mature fields, with large amounts of remaining oil in place but which also contain a high number of shut-in and abandoned wells. To help alleviate the problem of well-abandonment, the characterization procedures and geological and engineering models being developed in the course of this research are designed to provide near-term solutions that will directly benefit independent oil producers and integrated oil companies operating in similar types of reservoirs. For example, as a result of this work, the information needed to reposition water injection and production wells is available to operators to optimize production and potentially prevent further well abandonments. Evaluation of a proposed CO_2 pilot project for an independent operator is also being conducted.

Near- to mid-term applications of methodologies developed in this research can be used in the construction of accurate reservoir models to quantify the effects of reservoir heterogeneities. Long-term results of the research will determine the transferability of reservoir and production characteristics to reservoirs of similar depositional histories. Identification of heterogeneities in these reservoirs will allow application of newly developed reservoir management strategies and advanced recovery methods to maximize recovery efficiency. Because of the similarity between shoreline barrier and some delta-front depositional settings, the scope of future work may be expanded to include a comparison of reservoir heterogeneities from selected delta-related barriers with shoreline barriers.

Research Summary

This research project employs an interdisciplinary approach focusing on the high-priority reservoir class of shoreline barrier deposits: (1) to determine the problems specific to this class of reservoirs by identifying the reservoir heterogeneities that influence the movement and trapping of fluids and (2) to develop methods to effectively characterize this class of reservoirs to predict residual oil saturation (ROS) on interwell scales and improve the prediction of the flow patterns of injected and produced fluids.

As in previous years, an interdisciplinary team approach was used to characterize Patrick Draw (WY) field and to compare the geological and engineering models developed with models from Bell Creek (MT) field. Accurate descriptions of the spatial distribution of critical reservoir parameters (e.g., permeability, porosity, pore geometry, mineralogy, and oil saturation) are essential for designing and implementing processes to improve sweep efficiency and thereby increase oil recovery. The scope of the work for FY91 consisted of four main areas: (1) development of quantitative geological and engineering models for Patrick Draw field, (2) comparison of the similarities and differences between the mesotidal shoreline barrier reservoir in Patrick Draw field and the microtidal shoreline barrier reservoir in Bell Creek field, (3) the application of geostatistical techniques such as kriging and fractal analysis to estimate interwell reservoir properties in Patrick Draw field, and (4) the continued development of methodologies for improved characterization of shoreline barrier reservoirs.

In the first area, reservoir and outcrop information was used to construct the quantitative geological shoreline barrier model for Patrick Draw field. Investigations indicate that mesotidal processes (2 to 4 m range) dominated the depositional setting at Patrick Draw field. Mesotidal shoreline barrier deposits contain laterally discontinuous sand bodies and are architecturally more complex than micro-tidal barriers. The work in FY91 provided additional detailed information about the reservoir model for Patrick Draw field.

Two broad permeability and porosity classes can be distinguished according to groups of facies. The higher permeability class consists of tidal inlet, tidal channel, and tidal delta facies and is consistent with the higher depositional energies of the facies. Low-permeability intervals within the high-permeability class appear to be the result of carbonate cementation, detrital clay, and clay cement. A lower permeability class consists of tidal creek, tidal flat, swamp, and lagoonal facies. The relative timing of various carbonate cement phases (such as calcite, dolomite/ankerite, and siderite) plays a significant role in determining rock quality. Early carbonate cements strengthened the reservoir rock, preventing or delaying compaction; however, large amounts of cement drastically reduced the storage capacity of the reservoir sandstones and created permeability barriers affecting fluid flow.

Major depositional features of the Almond formation within Arch Unit, Patrick Draw field that are important to fluid flow consist of: (1) sand-thin areas containing low-permeability sediments made up of oyster coquina, carbonaceous shale, and shaley sand; (2) sand-thick areas containing superior reservoir rock quality; (3) facies with limited lateral extent (10's to 1,000's of ft); (4) coal beds prone to parting and fracturing during fluid injection; and (5) calcite cemented oyster-shell zones.

Lithologic controls on reservoir quality consist of the relatively high proportion of sedimentary rock fragments within the sandstones (average of 16% of total framework grains) which are highly susceptible to compaction and thus reduce permeability. Structural controls on reservoir behavior include faults and fractures. Interpretation of high resolution seismic sections and log-based structural cross-sections through Arch Unit indicate the presence of faults with vertical displacements of 20 to 50 ft. The orientations and distributions of these faults are currently being determined. Carbonate-filled fractures in cores have been documented; however, the effect of fractures on production behavior in Patrick Draw field is not well understood at this time.

Lateral compartmentalization within the reservoir is indicated by large contrasts in formation water salinity, with anomalously lower salinities downdip in deeper parts of the reservoir; and an anomalously large decrease of formation pressure during primary production in the eastern (downdip) portion of the reservoir. The mechanisms controlling these anomalies are currently being investigated.

Primary and secondary production/injection data were used to construct the engineering model for Patrick Draw field. Analysis of primary production data indicated that initial production (IP) was controlled predominantly by thickness of the sandstone. However, structural features, such as faults or fractures, undoubtedly played a role in the distribution of cumulative primary production. Channeling and poor waterflood sweep efficiency in Arch Unit were indicated by low waterflood recovery and rapid breakthrough times. Fractures were the suspected conduits to fluid flow because matrix permeability contrasts were not high enough to cause such severe channeling.

The second FY91 objective was to compare the microtidal shoreline system of the Muddy formation with the mesotidal shoreline barrier system of the Almond formation. The results of this comparison indicated Almond formation shoreline barrier deposits have a facies architecture that is characterized by short barrier island segments separated by abundant tidal inlets. Tidal inlet fill, tidal delta, and tidal channel/tidal creek deposits are all well represented at Patrick Draw and in the analogous outcrops. Lateral migration of the tidal inlets is the dominant process leading to formation of a broad belt behind the barrier dominated by tidal delta and tidal channel deposits. The dimensions of facies within the mesotidal system at Patrick Draw field are generally smaller than those for the microtidal shoreline barrier systems at Bell Creek field.

Important similarities found between the shoreline barrier reservoirs in Patrick Draw and Bell Creek fields were: (1) both reservoir systems are compartmentalized on a field scale—Bell Creek field has six major producing units and Patrick Draw field has three; (2) pay thicknesses are comparable—23 ft in Bell Creek and 20 ft in Patrick Draw; (3) initial production in both reservoirs appeared to be strongly influenced by the architecture of the depositional systems, while secondary and tertiary production appeared to be more strongly controlled by structural and diagenetic features; and (4) faults played an important role in both reservoirs and contributed to poor sweep efficiency during waterflooding. Significant differences found between Patrick Draw field and Bell Creek field were: (1) diagenetic processes and timing were different, and in Bell Creek field, early stage leaching created oversized pores and enhanced reservoir quality (average permeability is 2,250 mD, average porosity is 28.5%), while in Patrick Draw field, early stage leaching was relatively insignificant, but later stage cementation by carbonates and clays significantly degraded reservoir quality (average permeability is 36 mD, average porosity is 19.6%); (2) the scale of major depositional heterogeneities differs due to the different depositional processes—in the micro-tidal Bell Creek field, major heterogeneities are on the scale of thousands of feet along the depositional strike, whereas in the mesotidal Patrick Draw field, the scale is commonly tens to hundreds of feet; and (3) the production mechanism in Bell Creek field was solution gas drive, whereas in Patrick Draw field oil production resulted from a strong gas-cap drive.

The mean grain sizes for Muddy and Almond formation depositional facies are similar. Sorting of Muddy and Almond formation sandstones also overlaps; however, Almond facies have a much larger range of sorting than do facies from the Muddy formation. These differences reflect different suites of facies that were created by different intensities of wave and tidal depositional processes. The trend of increased grain size with decreased sorting for both Almond and Muddy formations probably represents a fundamental relationship caused by availability of a wider range of grain sizes for the coarser samples.

The lithological and mineralogical compositions of Bell Creek and Patrick Draw reservoir sandstones are a function of both initial lithologies and diagenetic history. Relatively larger amounts of clay-rich sedimentary rock fragments in the Almond formation make the UA-5 reservoir at Patrick Draw field more susceptible to compaction and reduced pore throat sizes, while the distribution and crystallographic habits of kaolinite and illite in the Muddy formation make the reservoir rocks at Bell Creek field sensitive to the migration of fines during completion and production.

The third area of investigation for FY91 consisted of geostatistical analysis of permeability data of the subsurface (Patrick Draw field) and outcrop shoreline barrier Upper Almond formation. More than 600 permeability data, spaced 1 to 3 in. apart, were measured from an outcrop core. Based on variogram analysis of these data, a vertical correlation length for permeability values was found to be between 18 and 27 ft, which is approximately the thickness of one barrier island depositional cycle. Variograms and cross-variograms developed for permeability will be used for mapping interwell porosity and permeability using kriging and co-kriging techniques.

The fourth area addressed was an investigation of economical methods for shoreline barrier/barrier island reservoir description and simulation (methodology development). Two activities were undertaken: (1) development and testing of a minipermeameter for application of geostatistical techniques to reservoir and outcrop rock samples and (2) wireline log analysis of the effect of subsurface stresses on fluid production at Patrick Draw. The wireline log investigation of subsurface stresses found that: (1) a good estimation of overburden stresses can be obtained from integration of density log data and (2) at Patrick Draw field, variation of shale resistivity with depth is a function of the amount of water in the pores and is also dependent on the salinity of the formation water.

Process Utilization and Technology Transfer

With expertise developed over the past several years, the BE1 project staff has been called upon to conduct additional research for the DOE under the SGP Program. Topics addressed during FY91 were in important areas, outside the scope of the Base Program, that provided research data consistent with objectives of the AORPIP.

One SGP project had the objective of expanding inflow performance relationships (IPRs) to horizontal and slanted oil wells producing from solution-gas drive. The work followed that of Vogel (*J. Pet. Tech.*, Jan. 1968) who developed successful procedures for determining oil well productivity of vertical wells producing under solution-gas drive. In developing IPRs for horizontal and slanted wells, NIPER scientists employed a specially designed vertical/horizontal/slanted well reservoir simulator that allowed the determination of IPRs under a variety of reservoir and well parameters. In addition to the simulation studies, the project scope of work calls for the preparation of a

"User's Manual" for determining IPRs on a personal computer. Both the manual and results of the simulation studies are scheduled for publication early in FY92.

A second SGP project provided the DOE with geological and production characteristics of Class 1, clastic deltaic system reservoirs receiving top priority for study as outlined in the AORPIP. Documentation of this work included a summation of presentations given at a symposium on Class 1 fluvial-dominated deltaic reservoirs and the key points of audience discussion, followed by a literature-based summary of general reservoir characteristics and properties of deltaic deposits. Specific topics included a general review of the sedimentological aspects of deltaic systems; a discussion of reservoir heterogeneities related to deltaic depositional processes and the effect of fluid movement within the reservoir; a review of geological factors affecting recovery in 26 EOR pilot projects; and a description of the average reservoir properties and production characteristics derived from data acquired on 229 fluvial-dominated, unstructured deltaic reservoirs in the Tertiary Oil Recovery Information System (TORIS) data base. The document contained over 300 annotated references on deltaic deposits and reservoirs, which should greatly aid future research on deltaic reservoirs.

The objective of a third SGP project was to determine the degree of hydraulic communication and fluid flow between productive reservoir horizons using naturally occurring stable and radioactive isotopes. The emphasis of the first phase of the project was to conduct a literature review (1) to seek evidence of dynamic conditions and crossflow associated with multireservoir systems, (2) to identify which stable and environmentally acceptable radioactive isotopes were best suited for studying crossflow phenomena, (3) to review successful field applications where cross-formational flow was identified by geochemical isotopic techniques, and (4) to identify major field-specific aspects of conjectural cross-formational fluid migration and mixing in candidate oil and gas fields preselected for demonstrating the method. Results of the study showed that (1) leakage of hydrocarbons between horizons through geologic discontinuities may negatively affect all production stages and (2) the isotopic analysis technique is effective in identifying interformational cross flow in those instances where the use of conventional methods would be difficult and expensive.

A fourth SGP project was established to develop techniques for determining clay content and lithology of sandstone reservoirs from wireline log data. Correlations of log signatures with CT-scan density and measurements from X-ray defraction, scanning-electron-microscopic, and pretographic-imaging analyses were conducted to determine the clay characteristics and the ultimate effect of different clays on the log signatures. Investigations were conducted to determine the role of mathematical and/or statistical calculations of logs in identifying the types and volumes of clay materials present in sandstone reservoirs. Logs were analyzed from Bell Creek and Patrick Draw fields, and the results indicated that the distribution of power in the log data, as a function of frequency (power spectrum), gave high values at low frequencies; and that the characteristic distribution of power with frequency provided a good measure of the overall clay content and lithologic heterogeneities in sandstone reservoirs.

Late in FY91, a new SGP project was initiated to provide technical support to DOE's Naval Petroleum Reserve No. 3 operations at Teapot Dome (WY) field. The objective of this project is to apply NIPER's integrated multidisciplinary approach to reservoir characterization and EOR process design and simulation to enhance oil recovery in NPR No. 3 reservoirs. Emphasis is to be placed on three primary tasks: (1) use of surfactant additives to improve sweep efficiency in ongoing steamflooding projects in Shannon reservoir, (2) evaluation of the density and distribution of fractures in Shannon sandstone, and (3) orientation of technology transfer mechanisms to ensure effective problem solving, laboratory testing, and data analysis.

Seminars and Training

A 3-day field seminar was conducted for three geologists from a major oil company who were interested in Shannon outcrop fromations north of Casper, Wyo. NIPER's characterization of these outcrops began in 1985 as part of the research for the DOE-sponsored BE1 project on Reservoir Assessment and Characterization and continued as a 2-year, multi-client, industry-sponsored project "Quantified Spatial Variations of Reservoir Parameters" from 1988-90. The above-mentioned oil company participated in the industry-sponsored multiclient project in 1990, where permeability and porosity from closely spaced core plugs were used to determine the effect of the spatial arrangement and density of core-plug scale permeability data on waterflood efficiency. Sedimentological, diagenetic, and structural features of the Shannon were reviewed, as well as the attendant petrophysical properties.

A 7-day field seminar and 3-month, on-site training course were conducted for two scientists from the Scientific Research Institute of Petroleum Exploration and Development, Beijing, China. This field seminar was conducted on Almond outcrops in the Rock Springs, Wyo., area and addressed methods of data collection to include rock descriptions and the measurement of geologic sections. Three days were spent at the U.S. Geological Survey core repository, which houses over 1 million ft of core material. During this time, training was provided on methods of core description, documentation, and sampling for instrumental and petrophysical analyses. Activities during the 3-month, on-site training included instruction on the use and design of the minipermeameter, ways in which geostatistical methods are used for mapping reservoir parameters, and how the trainees perceived NIPER's research in relation to the geologic work being performed in China.

Publications

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Presentations

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Determination of Favorable Areas for EOR From Differential Oil-in-Place Calculations in Bell Creek Field, Montana, by A.M. Cheng and B. Sharma. Pres. at the SPE Joint Rocky Mountain Regional Meeting and Low Permeability Reservoir Symposium, Denver, CO, Apr. 15-17, 1991.

Studies of the Effects of Crossflow and Initiation Time of a Polymer Gel Treatment on Oil Recovery in a Waterflood Using a Permeability Modification Simulator, by M.M. Chang, H.W. Gao, T.E. Burchfield, and M.K.Tham. Pres. at Dept. of Pet. Eng., Colorado School of Mines, Sept. 19, 1991.

TORIS RESEARCH SUPPORT

Principal Investigator:	James F. Pautz
BPO Project Monitor:	Chandra Nautiyal
Project No.:	BE2
Funding for FY91:	$340,000 (EOR-Light Oil)
Period of Performance:	October 1, 1990 – September 30, 1991

Objective

The objective of this project is to provide research support to DOE's Tertiary Oil Recovery Information System (TORIS) in the areas of EOR project and reservoir data base management, EOR project technology trends analysis, and computer simulation.

Research Summary

Information acquired in this project concerning ongoing EOR projects and EOR technology is used to continually update the TORIS-EOR Project Data Base. Providing the DOE with current information on EOR projects helps to improve the understanding of specific EOR technologies and how and where these technologies are being applied.

Since 1982, the DOE has collected data from operators participating in the tertiary enhanced oil recovery incentives program. During FY91, data on these incentive projects for calendar year 1989 were entered into the two versions of the EOR project data base on computers located at the Bartlesville Project Office and at the Energy Information Administration in Washington, D.C. Monthly production data were entered on 59 projects for 1989 of which 56 continue to be active. Additional projects reported data for 1988 and 1987, bringing the total number reporting to 89 and 77 projects, respectively. Eighty incentive projects were reported as active at the end of 1987 and 70 projects at the end of 1988. Data were collected on 29 projects for 1990 and promised for another 28 projects. Before being entered into the data bases, these data undergo several phases of verification: visual checking of the accuracy of data entry, comparison of several data fields of new data with data already in the data bases, checking of numeric and character format, and verification of annual production figures. A report on this work is scheduled for publication during the second quarter of FY92. To date, the data have been reviewed for accuracy, and information on project characteristics has been expanded by including data on geologic age and field discovery date. Graphs have been prepared for the production and injection data for approximately 160 incentive projects for which at least 2 years of data have been collected.

Trends in the application of EOR technology in the United States are analyzed annually to determine significant technological changes. These analyses are based on current literature, the news media, and the project data bases that contain information on over 1,300 projects. Changes in the frequency, EOR process type, and reservoir characteristics of project starts show how the application of EOR is progressing. Data on 32 new EOR project starts were added to the data base during FY91. Between 1981 and 1988, the number of project starts declined corresponding to a decline in oil prices. The figure for 1989, 22 new starts, indicated a modest recovery in EOR activity as a result of increasing oil prices since 1987 but again dropped to a low of 12 new projects in both 1988 and 1990. Changes in project starts usually lag behind changes in oil prices. Polymer flooding projects have decreased both in actual numbers and relative to other EOR methods since 1986. Implementation of the longer-term, higher-cost methods such as CO_2 flooding in West Texas and steamflooding in California is continuing. The correlation of project starts with oil price is shown in figure 2.

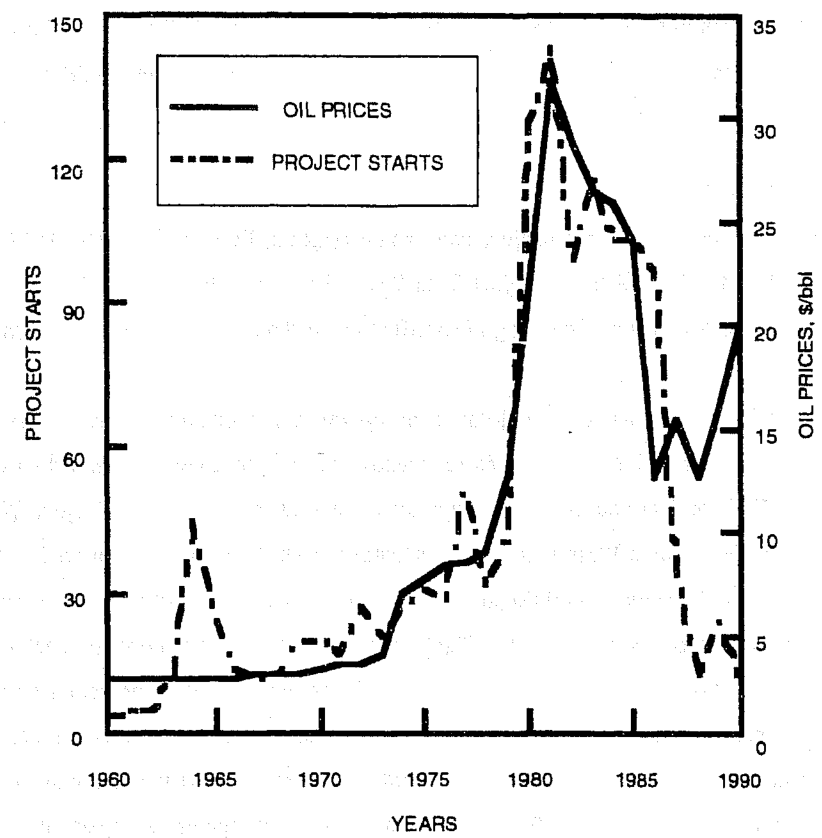

FIGURE 2. - EOR projects starts compared to oil price (refiner's cost).

Although the number of EOR project starts has declined drastically since 1986, production due to EOR has not declined correspondingly. In fact, production at the end of 1989 was 18% higher than that in 1986 when oil prices dropped by 50%. Production from both chemical and thermal methods has decreased, while production from gas projects has increased. EOR is being implemented selectively when it fits in with existing long-term plans and where the necessary extensive infrastructure exists. The trends indicate continued application of EOR in spite of price decreases. A comparison of the production from various EOR methods is presented in figure 3.

The interest in novel EOR technologies (microbial EOR, mine-assisted EOR, radio frequency oil production, alkaline/surfactant/polymer processes, etc.) is continuing at a low, but increasing level. Plans for microbial EOR projects continue, and applications that incorporate horizontal drilling are being considered. Field applications of these novel methods are cautious and on a small scale.

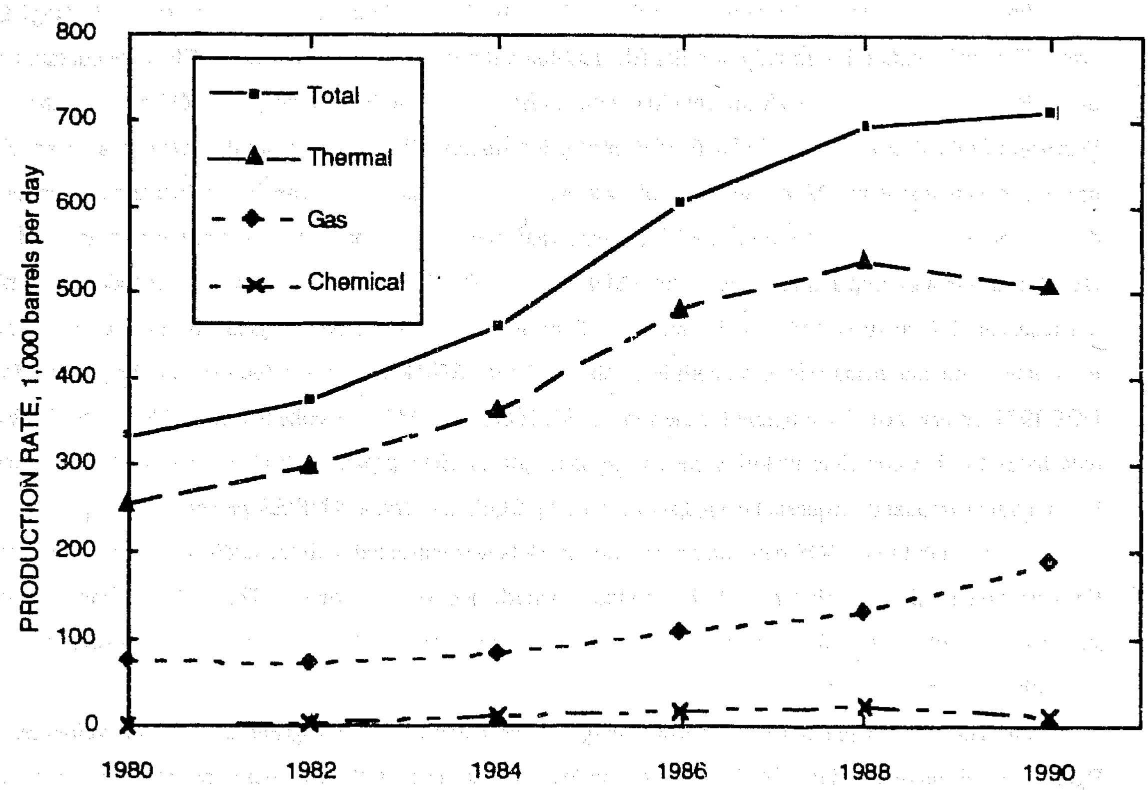

FIGURE 3.- EOR Production in the United States, including Alaska.

Inquiries concerning the operation of the DOE's publicly available simulators such as BOAST, BOAST-II, and MASTER are addressed by project staff as requested by the DOE. These simulators are the part of TORIS used by industry to model reservoirs and thereby determine the best solution to production problems before applying a specific process in the field.

Process Utilization and Technology Transfer

Other Base Program projects use the information gained in project BE2. Information on the various types of EOR projects and known reservoir characteristics is used to guide the direction of research. For the application of a new process, general screening criteria are compared to characteristics contained in the data base to determine the most compatible type of reservoir. Knowledge of the application of EOR for general process types, as well as for specific projects, helps identify the best direction for future research.

One SGP project in particular, which is designed to determine the geological and production characteristics of Class I reservoirs (top priority Class outlined for study in the AORPIP), relies heavily on the updated information provided to the TORIS data bases. The application and success (or lack of success) of a particular reservoir class need to be considered in developing the future course of EOR research.

Improving the availability of reservoir data to both the DOE and industry is an important technology transfer issue. This information is currently in a flat file, and limited retrieval capabilities exist. The data contain a mix of public information and proprietary information obtained from companies during the 1984 EOR study by the National Petroleum Council and now used in DOE EOR production studies. The goal is to put the data into an expanded data base management system (DBMS) that will allow broader retrieval and storage capabilities while maintaining secure data. A preliminary design for a reservoir data base that uses the relational model common in many commercial DBMS systems was prepared for DOE under a SGP project. The design has provisions for expanded availability of the reservoir information collected by the TORIS program during the past 9 years by protecting proprietary information and enhancing search capabilities. Also under the SGP Program, production data for projects from the DOE 1978 tertiary incentive program for the years 1987, 1988, and 1989 were collected and added to the EOR project data bases to give complete histories on a wide spectrum of EOR projects—both successful and unsuccessful. Information is frequently requested from this data base by DOE, industry, and NIPER personnel.

The availability of DOE computer simulation models was enhanced with the addition of a personal computer (PC) version of BOAST that models horizontal, slanted, and vertical wells. The BOAST line of computer simulators is widely used by independent oil producers, educational faculties, and petroleum consultants to model reservoirs for improved oil production.

The TORIS EOR predictive models are being updated under the SGP program to assist in development of the DOE heavy oil recovery plan. The histories of thermal EOR projects in the data base are used to identify required modifications in the screening criteria and to improve predictability of oil production and economics in the two thermal processes—steam and in situ combustion.

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Recommendations for Modifying the TORIS Model to Improve EOR Prediction of Heavy Oil Reservoirs, by R.D. Thomas and J.F. Pautz. Dept. of Energy Report No. NIPER-579, Dec. 1991. Available from DOE Bartlesville Project Office, Bartlesville, OK.

THREE-PHASE RELATIVE PERMEABILITY

Principal Investigator: Daniel R. Maloney
BPO Project Manager: Edith C. Allison
Project No.: BE9
Funding for FY91: $300,000 (EOR-Light Oil)
Period of Performance: October 1, 1990 - September 30, 1991

Objective

The objectives of this project are to improve the reliability of laboratory measurements of three-phase relative permeability for steady- and unsteady-state conditions in core samples, and to investigate the influence of rock, fluid, and rock-fluid properties on two- and three-phase relative permeabilities.

Research Summary

During FY91, a laboratory investigation was conducted to determine relative permeabilities and other characteristics of a 260-mD fired Berea sandstone core sample. The mineralogical and physical characteristics of the sample were determined by X-ray diffraction measurements, thin section analyses, mercury injection tests, and centrifuge capillary pressure and wettability tests. These tests were performed to provide results for comparing rocks having different relative permeability characteristics. Two-phase unsteady-state and steady-state oil/water relative permeabilities were measured under several stress conditions. Resistivity characteristics of the rock were also evaluated during several of the oil/water tests. Oil/gas and gas/water relative permeabilities were measured during steady-state tests. Three-phase steady-state oil/gas/water tests were performed for six DDI (decreasing brine and oil saturations, increasing gas saturation) saturation trajectories in which the sample was not cleaned between saturation trajectories.

Comparisons of two- and three-phase relative permeabilities were made for samples tested at conditions with and without confining pressure. These comparisons were possible because the samples were tested under identical conditions. Although relative permeability results for samples confined at 500 and 3,200 psig were similar, relative permeability curves for unconfined samples were not identical to those of confined samples of the same rock. Applying specific test results (permeabilities, residual saturations, etc.) from unconfined core plugs to the study of specific reservoir processes, where high confining stresses are present, should be done with caution. Changes in pore dimensions and closure of microfractures with stress, as demonstrated by the characteristic decrease in pore volume with stress that most rocks exhibit, are probably responsible for many of the differences in the unconfined and confined test results. The application of some confining pressure is recommended, however, when test results must be related to reservoir-specific processes.

Results of relative permeabilities and resistivities measured during a waterflood test on the 260-mD rock did not agree with measurements from steady-state tests. Water retention at the outlet face of the rock, as shown by CT scans conducted during the flood, probably contributed heavily toward the erroneous nature of the unsteady-state relative permeability results. These findings showed that particular care should be taken when evaluating laboratory resistivity and relative permeability results from tests in which saturation conditions were nonuniform. Thin sections of the sample were also cut from the unconfined rock, allowing comparisons of pore size distributions from thin sections with permeability results.

The rock was not cleaned after each DDI saturation cycle during the three-phase tests. Instead, the rock was flooded with brine to drive the oil and gas saturations to residual conditions before starting a new saturation trajectory. Two- and three-phase relative permeabilities for each fluid phase were primarily affected by the saturation of that phase when the wetting phase (brine) was also present and for conditions of appreciable flow of all of the phases. Water relative permeability vs. water saturation results were similar for both two-phase and three-phase flow systems. This result, which indicates that the wetting phase relative permeability is a unique function of the wetting phase saturation, agrees with the results from other investigations. Within the range of saturation conditions imposed during the laboratory tests, gas relative permeability vs. gas saturation results were similar from two-phase gas-brine and three-phase gas-oil-brine tests. During these tests, gas relative permeabilities were primarily dependent upon gas saturations. Lower oil saturations were achieved during three-phase tests compared to two-phase results. Oil saturations as low as 20% were achieved with oil flowing in the three-phase system, whereas the residual oil saturations during two-phase oil/brine tests were approximately 37%. Since mobilization of the oil phase was possible at lower saturations in the three-phase system, as compared to the two-phase system, two-phase oil relative permeability data were inadequate for describing oil relative permeabilities at oil saturations close to or less than the two-phase residual oil saturation condition. With oil saturations greater than the two-phase residual oil condition, two- and three-phase oil relative permeability results were similar, and the three-phase oil results tended to fall within the two-phase oil hysteresis envelopes.

These results were further described in a topical report, entitled "Three-Phase Relative Permeabilities and Other Characteristics of 260-mD Fired Berea." Techniques for determining two- and three-phase saturation distributions using X-ray and microwave scanners and a mass-balance method for monitoring oil and brine production during oil/brine unsteady-state relative permeability tests are described in appendices of the topical report.

Process Utilization and Technology Transfer

Several projects were undertaken for various major domestic and international oil companies using the technology developed as part of this project. These industrial projects were proprietary; however, the breadth of the work included: formation damage investigations for corrosion and scale inhibitor selection, measurements of residual oil saturations for an offshore reservoir from centrifuge imbibition experiments, centrifuge capillary pressure and wettability experiments to characterize rock/fluid systems and to evaluate thermal effects on the shapes of capillary pressure vs. saturation curves and residual saturations, steady-state gas/brine measurements to provide data for predicting ultimate recovery from a gas reservoir, steady- and unsteady-state relative permeability measurements on rock from an offshore reservoir to provide data for determining the feasibility of field development, and steady-state relative permeability measurements on unconsolidated sand samples to provide data for reservoir engineering calculations for an offshore field. A scientist with INTEVEP (Venezuela) assisted in this project during FY91 and was assigned to NIPER as part of a training program sponsored by INTEVEP and the DOE.

Publications

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IMAGING TECHNIQUES APPLIED TO THE STUDY OF FLUIDS IN POROUS MEDIA

Principal Investigator: Liviu Tomutsa

BPO Project Manager: Robert E. Lemmon

Project No.: BE12

Funding for FY91: $545,000 (AE&PT)

Period of Performance: October 1, 1990 - September 30, 1991

Objective

The objectives of this project in FY91 were (1) to derive reservoir engineering parameters from computed tomography (CT) scanning, petrographic image analysis, and nuclear magnetic resonance imaging (NMRI); (2) to apply newly developed state-of-the-art imaging technologies to the characterization of DOE high-priority reservoirs; and (3) to transfer newly developed imaging technologies through an industry consortium organized to help plan, review, and participate in the research.

Research Summary

The primary goal of this project is to advance the understanding of fundamental processes involved in oil recovery by developing, refining, and applying cross-cutting (CT, NMR, and petrographic) imaging technologies. The techniques developed in this project are being used to characterize pore structures and surfaces, pore-to-core-scale heterogeneities, rock-fluid interactions, and distribution of fluids in reservoir rock during corefloods. The project supports reservoir description and advanced oil recovery research and development, especially in the areas of reservoir chemistry, physics, and rock-fluid interactions at the micro and macroscopic (pore-to-whole-core) scales. Techniques developed in this project have been applied to understanding the rock fabric of various facies, determining the effect of various polymer/surfactant combinations on oil recovery, characterizing and selecting the most representative core plugs for special core analyses, understanding the effect of fractures on EOR processes designed for industrial clients, characterizing formation heterogeneities and their relation to log responses, and determining the relationship between saturation distributions and the electrical resistivity of core samples. Other applications include estimates of water and gas content in coal samples from coal bed methane formations.

Computed Tomography Imaging

Computed tomography (CT) imagery is a powerful tool for nondestructive measurement of variations in rock properties and fluid saturations in reservoir rock. NIPER acquired a third-generation medical CT scanner during FY89; and in FY90, developed computer software to provide for quantitative measurement of oil and brine spatial-saturation distributions in cores during flow experiments. In addition, a CT-scanning method was developed for determining porosity distributions within porous media. The method has been expanded to integrate the permeability values generated by the petrographic image analysis (PIA) of thin sections with porosity distributions determined by CT measurement. This provides a reliable method for predicting permeability distribution within a core.

Coreflood simulations were performed to test the validity of the CT/PIA combination method of calculating core permeability distributions. The porosity and permeability data generated above were used as input for the black oil simulator BOAST-VHS. The agreement between the fluid saturations obtained by the CT scanner, shown in figure 4, and by the simulator, shown in figure 5, indicate the excellent potential for this permeability determination method for samples in which a good permeability-porosity correlation can be generated by PIA.

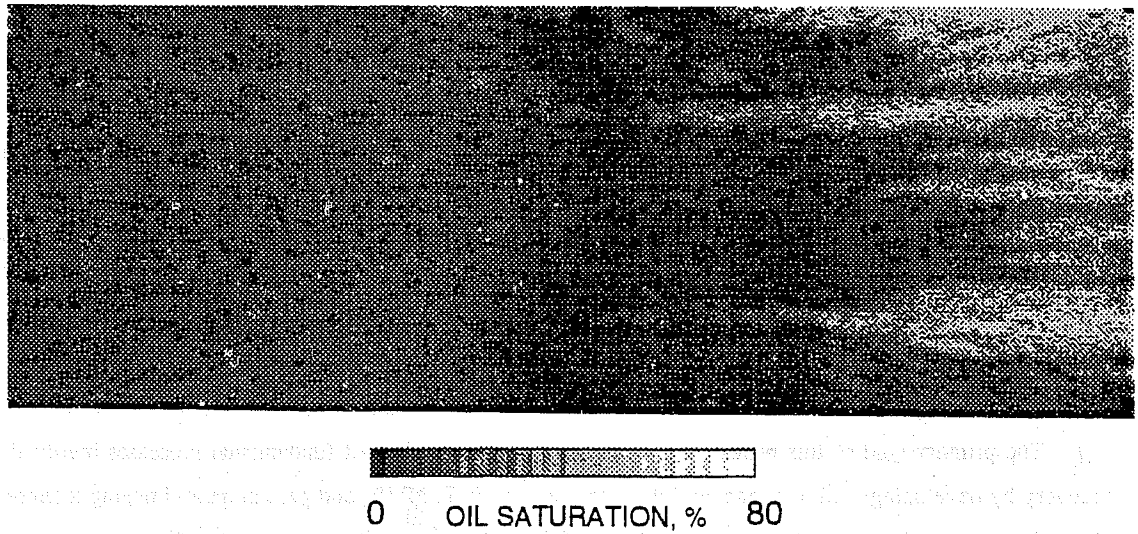

FIGURE 4. - CT scan of oil flood of Shannon sandstone (direction of flow is from right to left).

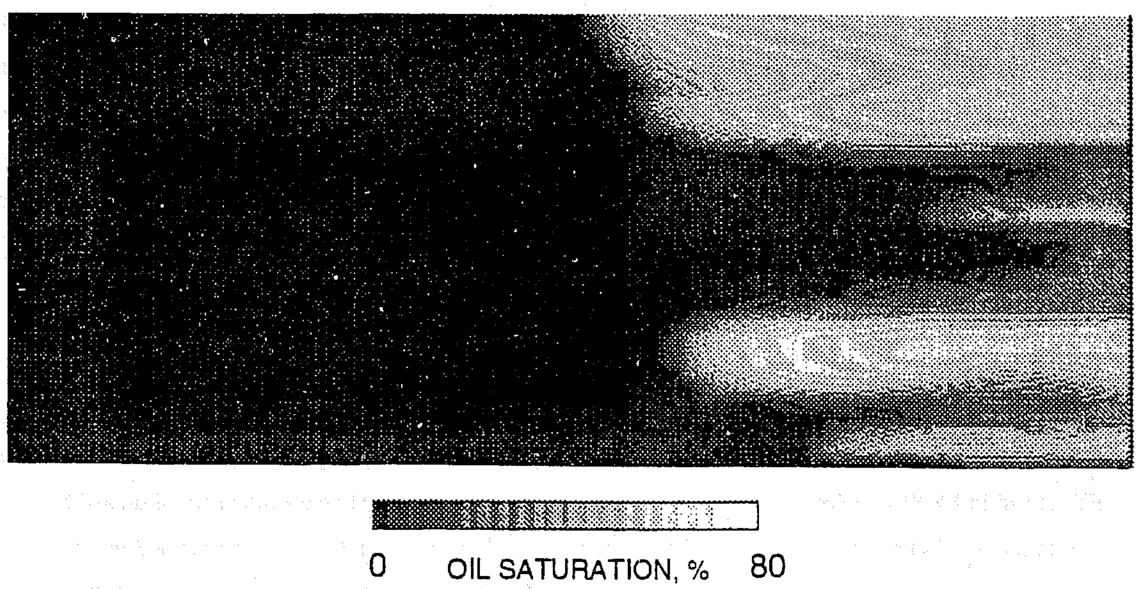

FIGURE 5. - Simulation of oil flood of Shannon sandstone (direction of flow is from right to left).

To measure the recovery efficiency of immiscible CO_2 floods and water-alternating-gas (WAG) recovery processes, accurate determination of spatial three-phase saturation distributions in reservoir rock are needed. To accommodate this need, methods were explored for measuring three-phase (gas, oil, and brine) saturations using the CT scanner. While CT scanning at one X-ray energy is adequate for porosity and two-phase saturation measurements in porous media, it is necessary in three-phase fluid saturation measurements that the media be scanned at two different X-ray energy levels. Dual energy equations were validated by comparing single and dual energy saturations at two-phase conditions. After establishing accurate porosity and two-phase results, a third phase (gas) was introduced into the rock, and three-phase saturations determined by the dual-energy method were compared to volumetric data. Good agreement (within 4%) was obtained between the two methods for three-phase systems and for average gas saturations of less than 35%.

Significant progress has been made in improving the versatility and efficiency of CT imaging technology at NIPER, and this has increased the demand for assistance of other projects performing research in the areas of multiphase fluid distributions in reservoir rock and in the characterization of core samples. To enhance the imaging capabilities and accommodate additional research work, the following technical improvements were made to the CT-imaging laboratory during FY91:

1. Interfacing of the CT scanner's host computer with a Macintosh IIfx-based image processing/analysis work station for rapid transfer of CT-generated images from the CT scanner to the image processing work station. This modification reduced transfer time of a single CT image from 8 minutes to 10 seconds.

2. Installation of a new, high-accuracy positioning system, with repeatability of 12.5 microns and total travel distance of 5 ft, for precise and simultaneous calculation of porosity and saturation distributions during multiple coreflood experiments.

3. Installation of three-dimensional (3-D) image analysis and processing software on the Macintosh work station to provide for rapid interpretation of the large quantity of spatial data generated during CT-scanning experiments. This processing software allows for rapid computation of porosity and saturation distribution and merging of two-dimensional (2-D) images into 3-D arrays. It also permits viewing of any 3-D arrays in sections along planes parallel to XY, XZ, and YZ planes as well as rotation of the 3-D object around the X, Y, and Z axes. Various color tables, as well as a gray scale, are available for data display. Porosity, permeability, and fluid saturations from CT applications have been readily displayed and analyzed, along with water and oil distributions at pore level from high-resolution NMRI studies.

Nuclear Magnetic Resonance Imaging

Nuclear magnetic resonance imaging (NMRI) is another nondestructive imaging technology used to image fluids within core. NIPER is at the forefront of NMR imaging developments in areas of spatial resolution, image processing techniques, and resolution of oil and water phases. A commercial high-resolution Fourier Transform NMR spectrometer has been modified by NIPER staff for use as an imaging instrument. During FY90 the instrument was used to generate 3-D images of fluids in beadpacks with resolution as low as 25 microns. Such resolution is required for the visualization of oil, water, and gas distributions within the pore spaces of reservoir rocks. This capability aids in understanding pore-level oil displacement processes and is essential for determining the mechanisms of oil recovery processes.

The FY91 research was designed to increase the spatial resolutions in rock samples toward the 20-micron range and was achieved by constructing a new gradient coil assembly that produces imaging gradients approximately seven times stronger than those previously attained. This modification was necessary for identification of pore level behavior of reservoir fluids under different oil recovery mechanisms. A new, more efficient, horizontal-coil NMRI probe was also installed. The radio-frequency (RF) coils can generate the shorter 90° RF pulses required for projection-reconstruction NMRI at higher gradients. The new probe also eliminates interferences from proton-containing materials used in the construction of standard NMR probes. The addition of a high-speed, two-channel A/D board and a 25-MHz 386 computer improved both data acquisition and processing time and permitted digitization of the higher bandwidth signals resulting from the stronger gradients achieved with the new gradient system. The horizontal solenoid NMRI sample probe was fitted with a new sample cell measuring 3 mm in diameter and 6 mm in length. The cell was calibrated using a water-saturated beadpack containing polymer beads in the 250 to 350 micron range. Images of the water protons were obtained at 128 x 128 x 128 and 256 x 256 x 256 pixels with corresponding pixel sizes of 30 and 15 microns, respectively. The pixel size of 15 microns represents the highest spatial resolution achieved to date by this laboratory. Using the new probe and gradient coil, NMRI images were obtained on fluids in a small plug of Bentheimer sandstone, 4 mm in diameter and 7 mm in length. At the highest resolution, the pixel size was 25 microns in the cross-sectional views with 40 microns along the axis. These images represent the highest resolution achievable to date for fluids in a sandstone. Soltrol mineral oil, with viscosity adjusted to 5 cP, was injected into the water-saturated Bentheimer plug. Two images of the plug were made at a pixel resolution of 256 x 256 x 256, one showing total fluid distribution (Fig. 6) and the second showing the residual water phase using an inversion recovery imaging sequence to null the oil phase signal (Fig. 7). Notice the water appears as small isolated droplets with virtually the entire pore space being filled with the oil phase.

Imaging Technology Applied to Other NIPER Projects

The following projects utilized CT imaging or petrographic image analysis (PIA) in deriving needed information not otherwise available.

1. Characterization of grain size distributions in reservoir and outcrop facies by PIA (Joint research with project BE1, Reservoir Assessment and Characterization).

The objective of project BE1 is to develop a methodology for the effective characterization of shoreline barrier reservoirs. For this development, an important part is played by the geological characterization of rock facies from different shoreline barrier reservoirs and corresponding outcrops. The grain size distribution measurement is a necessary component of rock description. By replacing the traditional manual point-count technique with computer-assisted PIA techniques, a larger number of rock thin sections could be analyzed, resulting in the generation of more

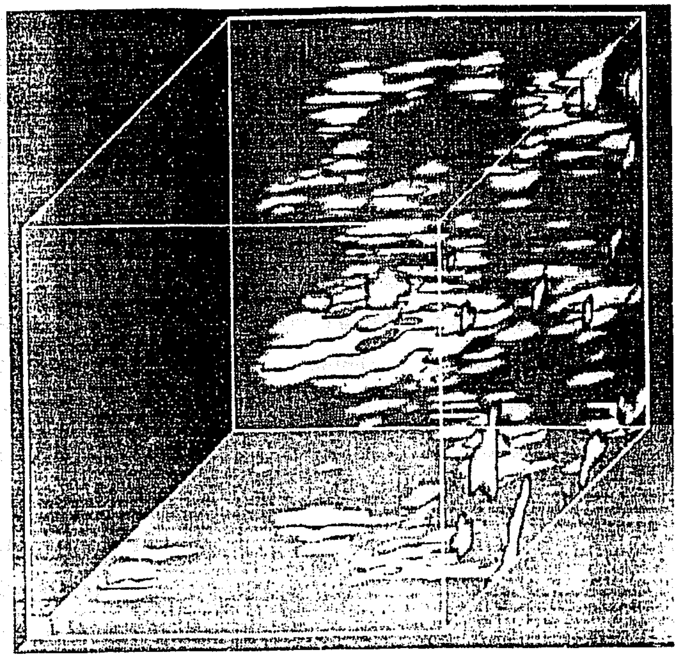

FIGURE 6. [illegible]

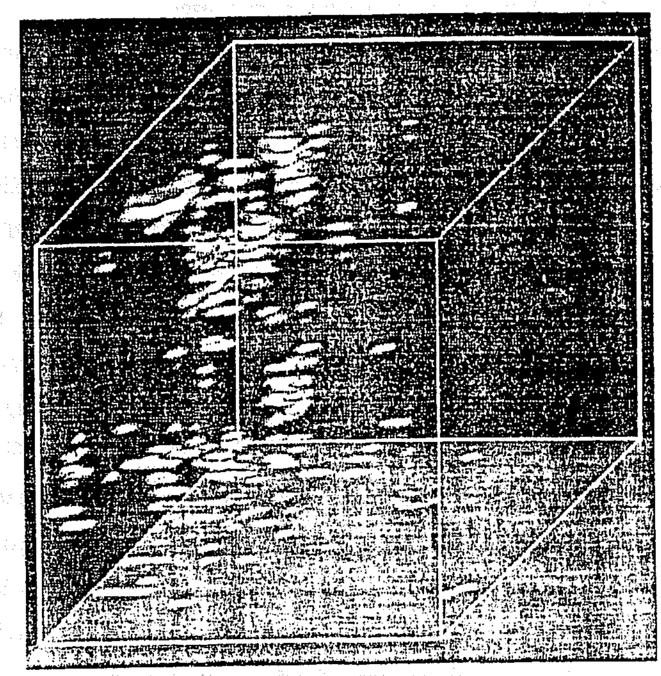

FIGURE 7. Pore space with [illegible]

representative data. Grain size and sorting were determined for a total of 75 thin sections prepared from cored wells located in Arch Unit of Patrick Draw field, situated in southwestern Wyoming, and from Almond formation outcrops located on the eastern flank of the Rock Springs Uplift, as close as 8 miles west of Patrick Draw field.

Grain sizes among combined Almond outcrop and subsurface samples range from coarse silt to fine sand (30-225 microns) and fall into two groups: (1) a finer-grained and better-sorted group comprising tidal creek and tidal flat facies, with the tidal flat mean grain size being consistently finer than all other facies and (2) a relatively coarser-grained and poorly sorted group, comprising all of the other facies including tidal delta, tidal channel, and tidal inlet facies. Tidal channel grain size distributions are similar for the outcrop and the subsurface samples, while tidal delta, tidal creek, and tidal inlet outcrop samples tend to be coarser grained than their subsurface counterparts. The crossplot of mean grain size vs. standard deviation of grain size (sorting) shows a linear relationship with a high correlation coefficient ($r = 0.95$) for outcrop as well as for subsurface data sets.

Mean grain size for the Almond formation (a mesotidal shoreline barrier system) lies in the 30-225 micron range, which is similar to the mean grain size for the Muddy formation (a microtidal shoreline system, previously studied in project BE1) which lies in the 95-150 micron range. On the other hand, the Muddy formation samples lack grains coarser than 150 microns, the outcrop and subsurface facies have very similar distributions, and the marine facies have a narrower range of sizes. Although the sorting for both formations is similar, the Almond formation facies have consistently poorer sorting than the equivalent Muddy formation facies. Also, both formations show similar good correlations between sorting and mean grain sizes.

2. Clay determination by log analysis (Joint research with Supplemental Government Program project entitled "Development of Methods for Mapping Distribution of Clays in Petroleum Reservoirs).

The presence of clay minerals has a great impact on petrophysical properties such as rock permeability and porosity. Their presence and type can be determined by thin section, XRD, and SEM analyses on reservoir cores but, due to costs, only a few wells are routinely cored while most of the wells drilled in a field are logged. Research to develop quantitative approaches to the use of logs for determining the presence of clays in a reservoir is being performed using both core and log data and mathematical analysis of this data. Since clays influence both the average density of the core and its mineralogy (two factors which affect X-ray attenuation), it is expected that CT scanning can be a useful tool in characterizing the rock. For example, CT scanning of a number of well-described whole cores from the Almond formation, Patrick Draw (WY) field, provided excellent correlations ($r \approx 0.98$) between the sonic density and CT density for the relatively homogeneous (uniform clay content) cores and lower correlations for the more heterogeneous cores. Small-scale (<1 in.) heterogeneities in the core (fractured, cemented, or clay-rich zones) were clearly apparent in the CT density profile, but their effect on the density log response was expected to be very small due to the effect of spatial averaging. Although, in general, the correlation between the CT density profile and the gamma ray log was excellent, the CT did not detect the presence of a thin shale layer that caused a gamma ray log response. This was probably due to the small density contrast between the shale and the neighboring sandstone.

3. CT imaging of surfactant/polymer floods (Joint research with project BE4A, Development of Improved Surfactant Flooding Methods).

Chemical flooding has the highest potential of all EOR processes for mobilizing residual crude oil from many U.S. domestic reservoirs because the chemical formulation of injected fluids can be varied to suit specific fluids and minerals for a given reservoir. The goal of NIPER research is to improve surfactant flooding methods of producing oil over a fairly broad set of conditions. The use of noninvasive rock-fluid imaging methods, such as CT, is needed to investigate the actual behavior of injected fluids within the rock during a flood. For a preliminary study in the application of CT to monitor chemical corefloods, two tests were conducted. The same surfactant formulation was used for both tests, but differed in that the surfactant injection was followed by injection of a mobility-control biopolymer with a concentration of 3,500 ppm in one coreflood and 1,200 ppm in the other. CT images showed strong differences in the oil saturation between the two floods. The flood with 3,500-ppm biopolymer concentration had high oil recovery, and formed an oil bank ahead of the surfactant slug. In the other test, no oil bank was observed, and a significant amount of oil was bypassed by the aqueous fluids. To understand the effect of rock on oil recovery, more information regarding the minerals present, the grain size, and pore and pore throat size distributions is needed from thin section, mercury injection, and XRD analyses.

4. Whole core screening by CT for selection of representative core plugs.

An important application of CT scanning is nondestructive evaluation of whole cores for selection of locations where representative core plugs should be taken. X-ray attenuations visible in the CT image are controlled by the porosity and the mineralogy of the rock. In proprietary work, CT scanning was used to screen 30 ft of core for selection of core plug samples for chemical flooding and to understand the low recovery measured in the floods performed on some of the selected core plugs. Highly fractured zones and the extent of the fractures were identified and provided explanations for chemical flooding recovery results.

Process Utilization and Technology Transfer

The rock-fluid imaging technology developed at NIPER can be beneficial to the oil industry as it contributes to a better understanding of fundamental oil recovery phenomena. When used in conjunction with other technologies available at NIPER, the imaging capability allows a more in-depth analysis of the diverse EOR processes being studied under the Base Program. CT monitoring of front movements in surfactant/polymer floods provides information regarding the interaction of the chemical system with the oil present in the rock, identifies the location of the bypassed oil, and helps in the design of the most effective EOR processes for a given reservoir. CT screening of whole core provides information necessary for the selection of representative core plugs. Permeability distributions within cores, obtained from correlations of petrographic image analysis measurements and combined with porosity distributions from CT scanning, provide data for the accurate simulation of floods within cores and identify the role of rock heterogeneity on oil recovery.

For mid- and long-term research, CT contributes to developing techniques for identifying clays in cores from wireline logs, and computer-assisted PIA provides fast and accurate grain and pore size data needed in understanding similarities and differences between facies deposited in various depositional environments. Also, high-resolution NMRI microscopy helps in understanding pore structure and fluid distribution in pores and provides the information needed to understand the mechanisms controlling various oil recovery techniques and to design improved recovery technologies. NIPER's imaging capabilities are used in the characterization of cores for industrial clients participating in the WFO Program.

Attempts to form a consortium on imaging technology development, as planned for FY91, was unsuccessful due to the lack of industry participation. Additional technology transfer activities will be conducted in FY92.

Publications

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